ISSN 1068-798X, Russian Engineering Research, 2018, Vol. 38, No. 2, pp. 119–122. © Allerton Press, Inc., 2018.
Original Russian Text © G.M. Martinov, A.I. Obukhov, N.V. Kozak, 2017, published in STIN, 2017, No. 8, pp. 12–15.

The Usage of Error Compensation Tools of CNC for Vertical Milling Machines

G. M. Martinov, A. I. Obukhov, and N. V. Kozak*

Stankin Moscow State Technical University, Moscow, Russia

**e-mail: kozak@ncsystems.ru*

Abstract—The error of metal-cutting machines must be kept within standard limits when a numerical control system is first introduced. A mechanism for more precise control of the motion is proposed on the basis of control modules in the core of the CNC. The results of using the proposed approach when the AxiOMA Control numerical control system is introduced at the Quaser MV184 machine tool (produced by “KEMZ” Ltd.) are outlined.

Keywords: numerical control system, motion control, interpolation, machining error, compensation tables, jerk limitation, contour deviation

DOI: 10.3103/S1068798X18020120

MACHINING PRECISION ON INTRODUCING A CNC SYSTEM

Currently available computers permit the resolution of longstanding problems in the development of CNC software [1]. Previously, submicronic precision in calculating the command signals required continued complication of the control algorithms. In particular, highly specialized algorithms for calculating the acceleration and deceleration profiles were required for various types of contours. Current hardware permits dramatic simplification of the formulation of control signals for servo drives, by contour linearization and conveyer processing of elementary trajectory segments [2]. This approach is adopted in the AxiOMA Control numerical control system [3, 4].

The generation of ideal position and velocity signals is now possible even for nanometer precision. At present, it is not sufficient to transmit the calculated command values to the drives in order to ensure high machining precision. The factors that determine the machining precision are the errors in machine-tool manufacture and assembly, the constraints on the drive power, and inertia of the feedback loops.

Measures to increase the precision of CNC metal-cutting machines may be developed in two stages:

(1) ensuring static positional accuracy;

(2) increasing the dynamic precision of contour motion.

The static accuracy is determined by the error in attaining the specified tool coordinates in steady conditions. Attainment of the permissible static error is the precondition for subsequent optimization of contour motion.

The static positional error is determined by the manufacturing precision and mutual position of the mechanical components of the machine tool responsible for motion of the tool relative to the workpiece (ball–screw pairs, guides, etc.); and by their dimensional stability with change in the temperature. The overall error of the mechanism is systematic and hence may be measured. On that basis, its compensation is relatively simple. For axes subject to constant load (for example, vertical axes), the parameters of the servo drives and their feedback loops may also have significant influence on the static precision, although that is usually taken into account in selecting the electrical equipment for the machine tool.

The dynamic precision depends on the speed of the feedback loops—that is, on their ability to respond to perturbations with minimum delay, by generating an appropriate compensation signal. A second important factor is the type of perturbation (most often static friction forces), which sharply changes the torque at the axis on passing through the dead points (where the velocity along the axis is zero).

Rapid progress in debugging CNC metal-cutting machines depends on the availability of convenient instruments for measuring the velocity and position of the axis [5]. In optimizing the static accuracy, one-time use of external measuring equipment (usually an interferometer) is required. In minimizing the dynamic error, by contrast, software in the CNC system is required to visualize the mass of sensor data in real time.

SOFTWARE TOOLS FOR MORE PRECISE MOTION CONTROL

The core of the AxiOMA Control numerical control system is based on modules for sequential process-

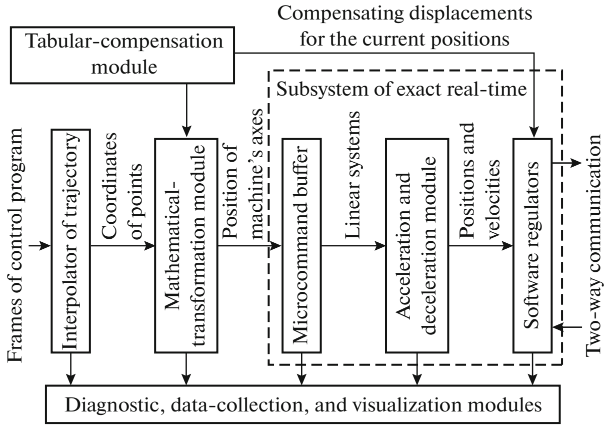

Fig. 1. Structure of the motion-control modules in the core of the CNC system.

ing of commands regarding motion over a specified contour. The structure of the basic control modules is shown in Fig. 1.

The interpolator of trajectory converts each frame of the control program into a set of points in the Cartesian coordinates of the metal-cutting machine [6]. Then the kinematic-converter module calculates the coordinates of these points in the axial system (that is, the position of the physical axes of the metal-cutting machine). Thus, we obtain an ideal trajectory in the axial coordinate system of the metal-cutting machine, in the form of a queue of linear motion microcommands.

Then, during the motion-control cycle in the real-time subsystem, the acceleration and deceleration module generates a timed sequence of increments in the drive positions on the basis of the microcommands, in accordance with the specified supply control law. Microcontrollers ensure velocity and position feedback and take account of the torque on the axis and the compensating motions. The calculated velocity and position signals are sent to the drives.

In this system, the following modules increase the shaping precision in the CNC metal-cutting machine.

- The mechanism for free specification of the rotary vectors of the circular axes in terms of the kinematic parameters, so as to ensure compensation of the nonstandard axis orientation. This is particularly important for five-coordinate metal-cutting machines [7, 8].
- The tabular compensation module, supporting uniaxial, temperature, transverse, and bulk compensation of the errors [9, 10].
- The algorithm for limitation of the jerk (the rate of change in the acceleration) in calculating the command velocity in acceleration and deceleration sections, with advance viewing of the control frames [11].

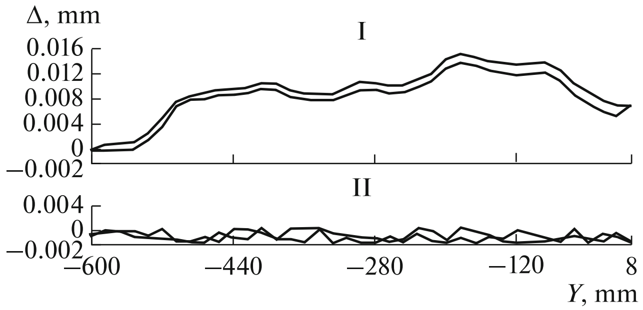

Fig. 2. Positioning error Δ along the *Y* axis before (I) and after (II) activation of the compensation table.

- Microcontrollers with a developed set of parameters, which monitor the errors at quadrant boundaries. Such microcontrollers in the core permit compensation of errors in the drives' feedback loops in some cases.

PRACTICAL APPLICATION OF PRECISION ENHANCEMENTS

We now present data regarding the installation and debugging of the AxiOMA Control numerical control system at the Quaser MV184 metal-cutting machine.

According to measurements by means of a laser interferometer (precision ±0.5 ppm in the range 0–40°C), the error in positioning the machine tool's axes (the positional deviation according to Sec. 3.5 of State Standard GOST 27843–2006) is of the order of 15–20 μm over the whole range of axial displacement (for example, 600 mm for the *Y* axis). Large error gradients are observed (up to 10 μm per 50 mm of length). The free play in each of the axes is no more than 2 μm. (That is the insensitivity zone in positioning according to Sec. 3.12 of State Standard GOST 27843–2006.) The results are introduced in tables for compensation of the nonuniformity in the screw pitch.

Subsequent measurements yield a result with stable reproducibility: the positional error is within ±1.5 μm over the whole interval. In Fig. 2, we show measurements of the positional deviation for the *Y* axis: (I) initial measurements; (II) results after application of the compensation tables. The position is plotted horizontally, while the error is plotted vertically. (The quantities are presented in mm.)

Note that, in debugging the CNC system, linear growth in positional error was observed with considerable temperature variation in the shop. (This does not occur in regular operation of the metal-cutting machine, by the way.) However, the lack of temperature sensors prevented the use of the temperature-compensation table.

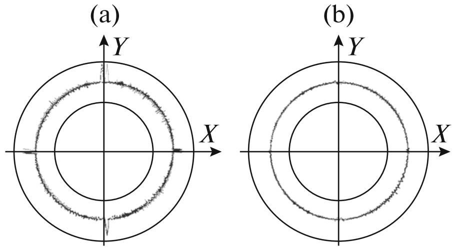

Fig. 3. Contour deviation for a circle in the *XY* plane before (a) and after (b) adjustment of the regulators, with compensation of the static friction.

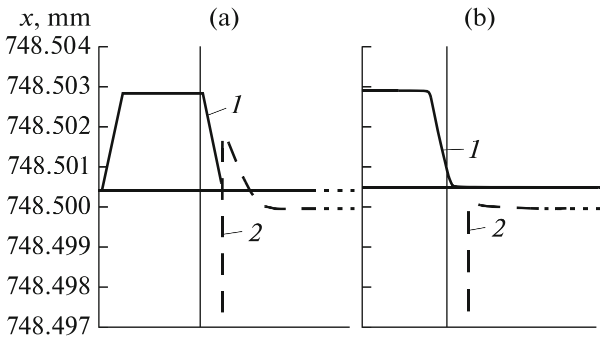

Fig. 4. Overrun along the *X* axis in linear deceleration (a) and deceleration with jerk limitation (b): (*1*) velocity; (*2*) position.

In the next stage, the microcontrollers are adjusted by means of a software-based digital oscillograph. Note two important points here.

(1) Selection of the maximum permissible constants of proportionality for the velocity and position feedback loops of the PID controllers [12]. Values ensuring minimum contour deviation in the absence of perceptible vibration of the axes are selected.

(2) Selection of times and multipliers for the static-friction compensators. These parameters determine the length and amplitude of the signals processed by the microcontrollers when the motion of the axes is reversed. That is necessary in order to minimize the errors at the quadrant boundaries [13].

In Fig. 3, we compare the test results for motion over a circle of diameter 70 mm when the supply is 1000 mm/min. The external and internal circles correspond to deviations of ±40 μm (the circular deviation *G* according to State Standard GOST ISO 230-4–2015, Sec.3.4). The data are obtained from the motor sensors.

Before microcontroller setup, the mean bidirectional deviation *D* (according to State Standard GOST ISO 230-4–2015, Sec. 3.6) is 8 μm, while the deviation *G* at the quadrant boundaries is 40 μm. After parameter selection, *D* declines to 4 μm, while the deviation *G* at the quadrant boundaries is practically indistinguishable against the background deviation. The circular deviation *G* over the whole contour is no more than 8 μm.

The results confirm that errors at the quadrant boundaries may be eliminated by a compensating triangular pulse of specified length and amplitude. However, the expected dependence of the optimal compensation parameters on the radius of the circle and the supply is also found.

To solve this problem, tabular specification of the compensator parameters in the system for different speeds and contour curvature is proposed, with training of the regulator by means of tabular values. Nevertheless, in that research, the quality of compensation may be regarded as satisfactory for the required interval of linear workpiece dimensions and the supply.

Another approach to optimizing the system precision is associated with introducing the velocity control, ensuring a limit on the jerk (the linear, rather than instantaneous, change in the acceleration on moving over the contour). In many cases, the drives and their feedback loops do not ensure the attainment of the specified position without some overrun in linear deceleration. Consequently, on approaching the contour, some incision in the workpiece may be noted. Such incision rarely exceeds a few microns but also makes a contribution to the overall machining error.

Quadratic acceleration and deceleration with a finite limit on the jerk may solve this problem. In Fig. 4, we show position measurements of the sensor for the X-axis motor, obtained by means of the digital oscillograph built into the CNC system. (The vertical scale is 1 μm/cell). In linear deceleration, the overrun is 2 μm. This value is practically independent of the supply. It depends only on the acceleration (1200 rpm/s in the present case). Activation of the limit on the jerk (at 12000 rpm/s) practically eliminates that overrun.

After such adjustments of the CNC system, test components are produced. Their measurement leads to the conclusion that the positional error in the machining of steel workpieces in standard cutting conditions is no more than 4 μm, while the deviation from the specified contour with linear and circular interpolation is no more than 10 μm. Since the metal-cutting machine was not initially equipped with linear position sensors (the intent was to use only motor sensors), the results are regarded as satisfactory.

CONCLUSIONS

(1) Two-stage optimization of the precision of CNC metal-cutting machine entails the use of the proposed diagnostic and visualization methods for the data obtained from the position and velocity sensors.

(2) Tabular compensation in the AxiOMA Control numerical control system considerably reduces the

systematic positioning errors due to the mechanical characteristics of the metal-cutting machine.

(3) The use of microcontrollers that support compensation of the static friction reduces the impact of faults in the drives' feedback loops and minimizes the errors at the quadrant boundaries, which are largely responsible for the error in curvilinear motion [14, 15].

(4) Limitation of the jerk proves very useful in optimizing the control system in terms of the machining precision. The overrun in deceleration may be eliminated.

(5) Even with no precise linear sensors, the resources of the CNC system permit standard errors of the metal-cutting machine in normal operation.

ACKNOWLEDGMENTS

Financial support was provided by the Russian Ministry of Education and Science (project 2.1237.2017/4.6).

REFERENCES

1. Grigoriev, S.N. and Martinov, G.M., An ARM-based multi-channel CNC solution for multi-tasking turning and milling machines, *Proc. CIRP*, 2016, vol. 46, pp. 525–528.
2. Martinov, G.M., Kozak, N.V., Nezhmetdinov, R.A., et al., Method of decomposition and synthesis of the custom CNC systems, *Autom. Remote Control* (Engl. Transl.), 2017, vol. 78, no. 3, pp. 525–536.
3. Martinova, L.I., Kozak, N.V., Nezhmetdinov, R.A., et al., The Russian multi-functional CNC system AxiOMA control: practical aspects of application, *Autom. Remote Control* (Engl. Transl.), 2015, vol. 76, no. 1, pp. 179–186.
4. Grigoriev, S.N. and Martinov, G.M., The control platform for decomposition and synthesis of specialized CNC systems, *Proc. CIRP*, 2016, vol. 41, pp. 858–863.
5. Grigor'ev, S.N. and Martinov, G.M., Adjustment and diagnostics of metal-cutting machines using Web technologies, *Avtom. Prom-sti*, 2014, no. 6, pp. 3–7.
6. Martinov, G.M. and Martinova, L.I.., Development of basic computer CNC platform for building specialized control systems, *Vestn. Mosk. Gos. Tekhnol. Univ., Stankin*, 2014, no. 1 (24), pp. 92–97.
7. Martinov, G.M. and Kozak, N.V., Specialized numerical control system for five-axis planning and milling center, *Russ. Eng. Res.*, 2016, vol. 36, no. 3, pp. 218–222.
8. Martinov, G.M. and Kozak, N.V., Numerical control of large precision machining centers by the AxiOMA control system, *Russ. Eng. Res.*, 2015, vol. 35, no. 7, pp. 534–538.
9. Martinov, G.M., Obuhov, A.I., Martinova L.I., et al., An approach to building a specialized CNC system for laser engraving machining, *Proc. CIRP*, 2016, vol. 41, pp. 998–1003.
10. Martinov, G.M., Obuhov, A.I., Martinova L. I., et al., An approach to building specialized CNC systems for non-traditional processes, *Proc. CIRP*, 2014, vol. 14, pp. 511–516.
11. Lyubimov, A.B., Martinova, L.I., and Obukhov, A.I., The algorithm of advanced scanning of frames for linear and non-linear feed control laws in CNC systems, *Avtom. Prom-sti*, 2016, no. 5, pp. 10–13.
12. Grigor'ev, S.N. and Martinov, G.M., Control and diagnostics of digital drives of CNC machines, *Kontrol. Diagn.*, 2012, no. 12, pp. 54–60.
13. van Geffen, V., *A Study of Friction Models and Friction Compensation, Technical Report DCT No. 2009.118*, Eindhoven: Univ. Technol., 2009, p. 24.
14. Martinova, L.I., Sokolov, S.S., and Nikishechkin, P.A., Tools for monitoring and parameter visualization in computer control systems of industrial robots, *Sixth Int. Conf. on Swarm Intelligence and the Second BRICS Congr. on Computational Intelligence (ICSI-CCI'2015)*, Tan, Y., et al., Eds., Beijing, 2015, vol. 9142, pp. 200–207.
15. Martinova, L.I., Pushkov, R.L., Kozak, N.V., and Trofimov, E.S., Solution to the problems of axle synchronization and exact positioning in a numerical control system, *Autom. Remote Control* (Engl. Transl.), 2014, vol. 75, no. 1, pp. 129–138.

Translated by Bernard Gilbert